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EVALUATION OF THE M 6700 RADAR D.F. ANTENNA

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EVALUATION OF THE M 6700 RADAR D.F. ANTENNA

by

K. O. Hornberg

August 1947

Problem No. 39R06-06

Approved by

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ABSTRACT

This report covers the evaluation of an experimental 5 kilomegacycle to 12 kilomegacycle radar direction finding antenna developed by the Radio Research Laboratory at Harvard University under NDRC Contract OEMsr-411. The purpose of this work was to evaluate the subject antenna as to its suitability for use with the DBM and DBM-1 radio and radar direction finding equipments to extend the frequency coverage of these equipments to 12 kilomegacycles.

The results indicate the general suitability of the M 6700 antenna for the purpose intended. Recommendations for certain minor changes are included.

PROBLEM STATUS

This report concludes the work on this problem. Unless the Bureau advises the Laboratory to the contrary, the problem will be closed one month from the mailing date of this report.

AUTHORIZATION

Work on this problem was requested by BuShips letters to NRL Serial 4-3414(925Dd) dated 17 May 1946 and Serial 4-3846(925Di) dated 29 August 1946.

EVALUATION OF THE M-6700 RADAR D. F. ANTENNA

INTRODUCTION

The work covered in this report was performed to evaluate the performance of the M 6700 experimental radar direction finding antenna covering the 5 kilomegacycle to 12 kilomegacycle frequency range and determine its suitability for use with the DBM and DBM-1 radio and radar direction finding equipments to extend the frequency coverage of these equipments to 12 kilomegacycles. This M 6700 antenna consists of a rotating reflector and a horn suitable for receiving either plane polarized or circularly polarized waves of the correct rotation. The horn will hereafter be referred to as circularly polarized.

A limited amount of time and the lack of suitable equipment, such as relatively high power, variable frequency transmitters required by the necessity of greater transmission distances for overall antenna tests, precluded a thorough evaluation over the entire frequency range. Overall antenna tests were thus limited to one frequency in the X-band (9.57 kilomegacycles), while the performance of the circularly polarized horn, which did not require such large transmission distances and consequently high power transmitters, was evaluated at several frequencies between 5.4 kilomegacycles and 10.3 kilomegacycles which was the top limit of frequency available. A flight test was conducted to determine the maximum range of bearing indication with an airborne AN/APS-4 X-band radar as the target.

GENERAL DESCRIPTION OF M 6700 RADAR D. F. ANTENNA

The M 6700 Radar D. F. Antenna, designed and fabricated by the Radio Research Laboratory at Harvard University under NDRC contract OEMsr-411, is a circularly polarized horn with a continuously rotating reflector and covers the frequency range from 5 kilomegacycles to 12 kilomegacycles. This antenna, which will accept signals of any plane polarization or a circularly polarized signal of the correct rotation, was designed for use with the DBM and DBM-1 radio and radar direction finding equipments to extend the frequency coverage to 12 kilomegacycles. Unlike the two DBM Antenna spinners covering the 90 megacycle to 5 kilomegacycle frequency range, the M 6700 spinner has no means of determining the signal polarization.

The direction of the source of intercepted signals is presented on the DBM or DBM-1 indicator cathode ray tube in the form of a polar plot of the antenna pattern with the maximum pointing to the direction of signal arrival. Reception of pulsed signals will cause this polar pattern to be filled in with radial lines.

The primary element of the M 6700 antenna is the circularly polarized horn which is mounted in a stationary position with its axis vertical so that the aperture points upward into the 45 degree inclined reflector which rotates about the horn. The reflector is a piece of sheet metal cut and bent to form a section of a parabolic cylinder and is driven by a motor through a gear train to which a 5-G Selsyn is also coupled, permitting the reflector orientation to be relayed to the indicator at the operating position.

Although the shape of the reflector is such that an accurate determination of its projected area is very difficult, an approximate projected area of 90 square inches can be given for rough comparison purposes with other antennas.

The entire antenna assembly is mounted on a cast aluminum pedestal and covered with a radome. The antenna including the radome is 29 inches in height and 15 inches in diameter. The entire equipment weighs approximately 30 pounds.

DESCRIPTION OF FIELD TEST SITE AND ASSOCIATED TEST EQUIPMENT

The portion of the M 6700 Radar D. F. Antenna evaluation which required a field installation was conducted at Blue Plains which is located about one mile south of this Laboratory along the Potomac River. The general area of the site is clear from all overhead or buried power cables for a considerable distance. Figures 1 through 4 are photographs of the site and the test equipment. The subject antenna was secured to a rotatable tripod and mounted on a deck on top of a two story building about twenty five feet above the ground.

The target transmitter, which was mounted on a telephone pole 100 feet away and at the same elevation as the receiving antenna, consisted of a high-power magnetron pulsed by an MIT Radiation Laboratory Model 12 Modulator, together with a 12-inch shallow parabolic reflector fed by a plane polarized horn and parasitic elements. The plane polarization characteristic of this transmitter was found to be greater than 40 decibels. In other words, a vertically polarized receiving antenna mounted 100 feet away gave an indicated output 40 decibles higher when it received vertically polarized transmitted signals than when the transmitted signals were horizontally polarized. Inasmuch as there were no magnetrons available capable of covering the entire frequency range, investigations involving the entire M 6700 antenna were limited to one frequency, 9.57 kilomegacycles.

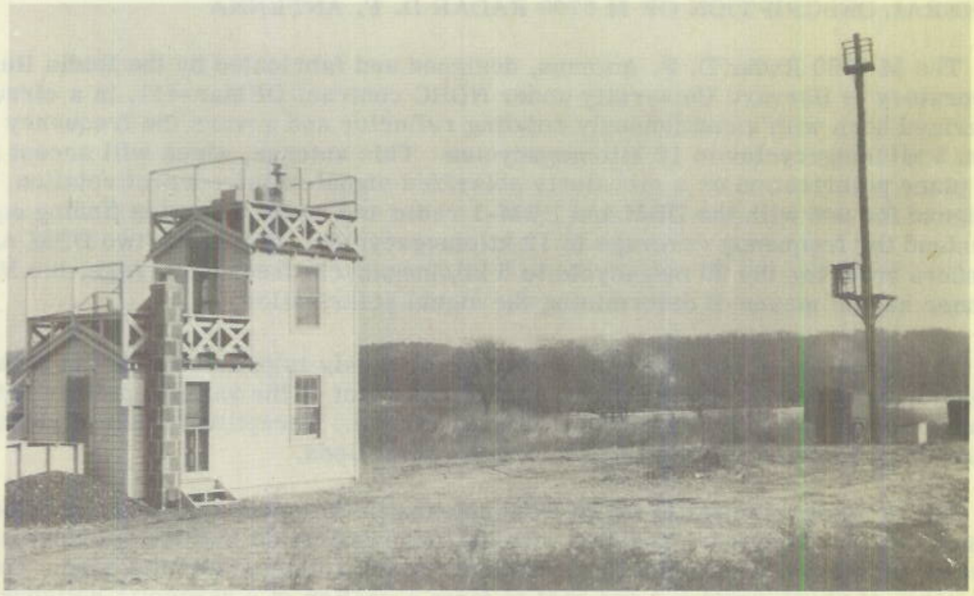

Fig. 1 - Test Site at Blue Plains

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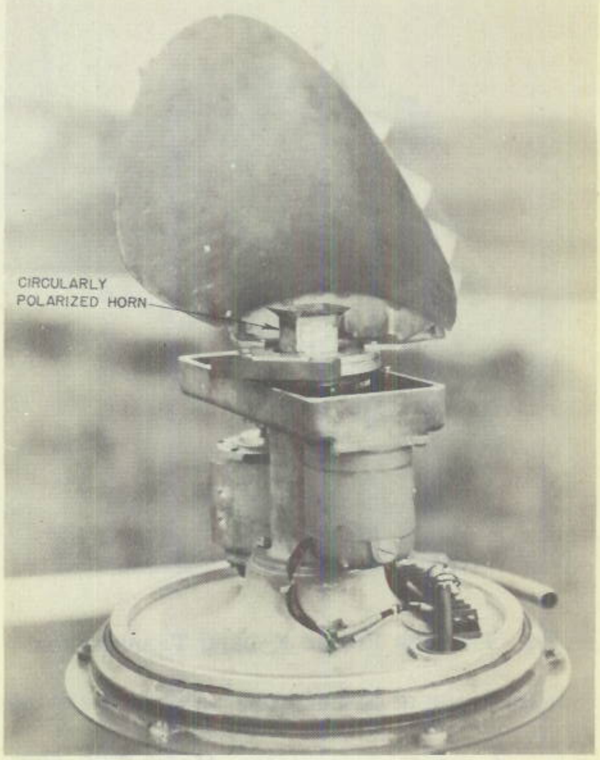

Fig. 2 - M 6700 Radar D. F. Antenna

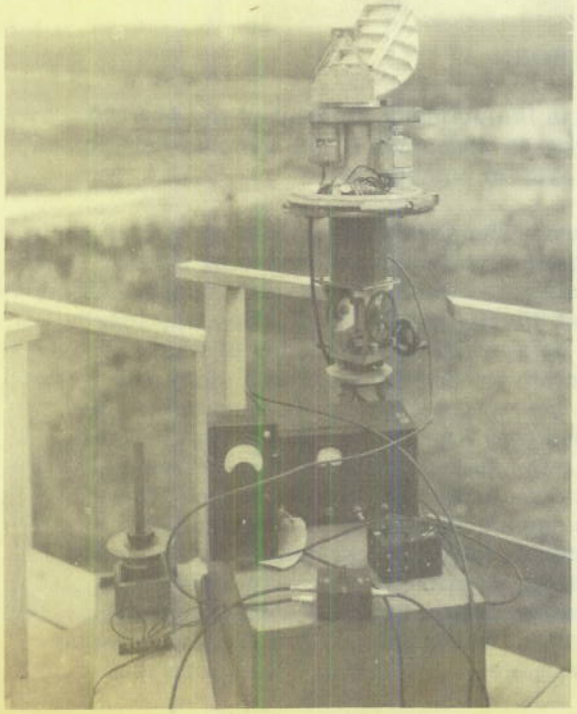

Fig. 3 M 6700 Antenna and Associated Test Equipment

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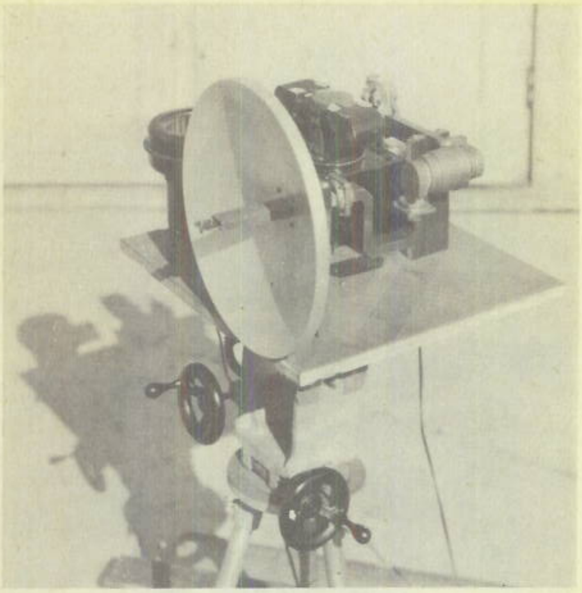

Fig. 4 - High Power X-band Transmitter

The method used in the gain evaluation of this antenna necessitated the design and construction of a bolometer detector and a triple stub tuner for matching purposes. Figure 5 is a photograph of this bolometer and triple stub tuner. A "bolometer", used in the measurement of radio frequency power is a device whose main property is that its resistance changes with temperature. Generally, an etched platinum wire is used for most bolometers. A modulated radio frequency signal will cause the resistance of this bolometer to vary at the modulation frequency, the changing resistance then being employed to modulate a small direct current providing an audio signal that can be amplified and observed. A tuned 1000 cycle linear amplifier and a Ballantine vacuum tube voltmeter were used in conjunction with the bolometer detector to give the relative power indication received by the antenna system. This method of signal detection was used in all tests made at Blue Plains unless otherwise stated under the separate sections.

A coaxial wavemeter, Model TFS-5TX, was used to determine the frequency of transmission used in the field tests which involved the entire M 6700 antenna. This wavemeter which utilizes a crystal detector was used with a pickup horn and a linear amplifier. By this means it was determined that the operating frequency was 9.57 kilomegacycles (a wavelength of 3.138 centimeters).

DESCRIPTION OF CIRCULARLY POLARIZED HORN

Inasmuch as the circularly polarized horn is the primary element of the M 6700 antenna system, a separate section is included as an addendum to the general description in order to describe better this important system component.

Figures 6 and 7 are photographs of this horn. The horn itself, consists of four parts, the flared aperture, the phasing or delay section, the polarizing or reducing section, and the rectangular waveguide feed. The flared aperture which is square in cross section is 2-1/16 inches on a side with a "flare angle" of approximately 90 degrees, the length of the flare being 7/16 inches. The phasing or delay section, the theory of which is included in the appendix, is square in cross section (1-15/32 inches on a side) and approximately 3-1/2 inches long. A dielectric wedge (polystyrene) is mounted in the center of the section parallel to one pair of sides (see Figure 7). This wedge is 9/64 inches thick and 3-1/2 inches overall in length. In order to reduce the impedance discontinuity, an isosceles right triangle is cut out of each end of this wedge. The polarizing or transforming section reduces the square waveguide to a rectangular waveguide and is shaped such that the square and rectangular waveguides are mounted at a 45 degree angle to each other. This polarizing section is approximately 1-3/8 inches in length. In order that this equipment may operate over the wide frequency range required, a 3/4 inch by 1-1/2 inch waveguide, which has a cutoff frequency below 5 kilomegacycles, is used. This section of waveguide is fitted with a flange so that

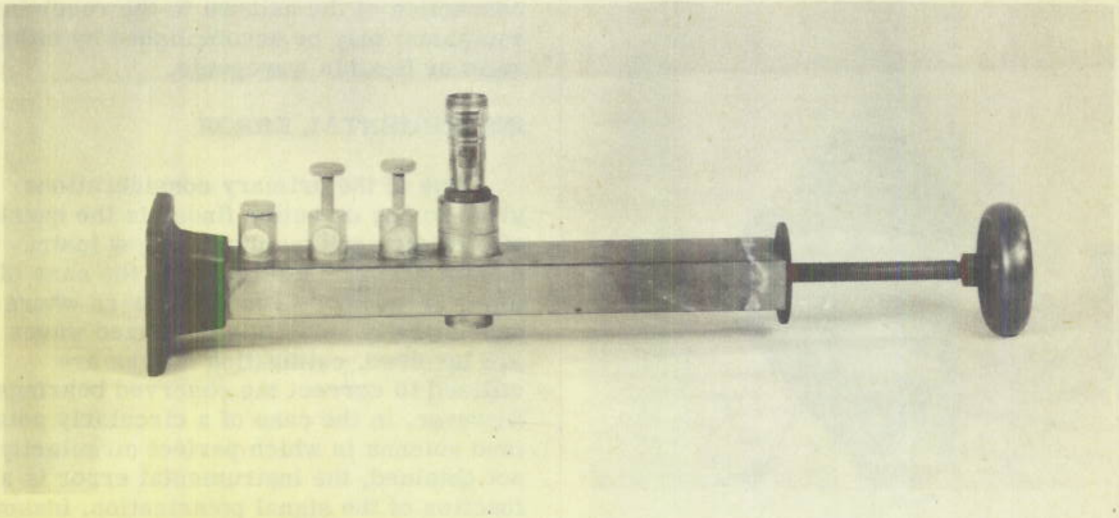

Fig. 5 - Bolometer and Triple Stub Tuner

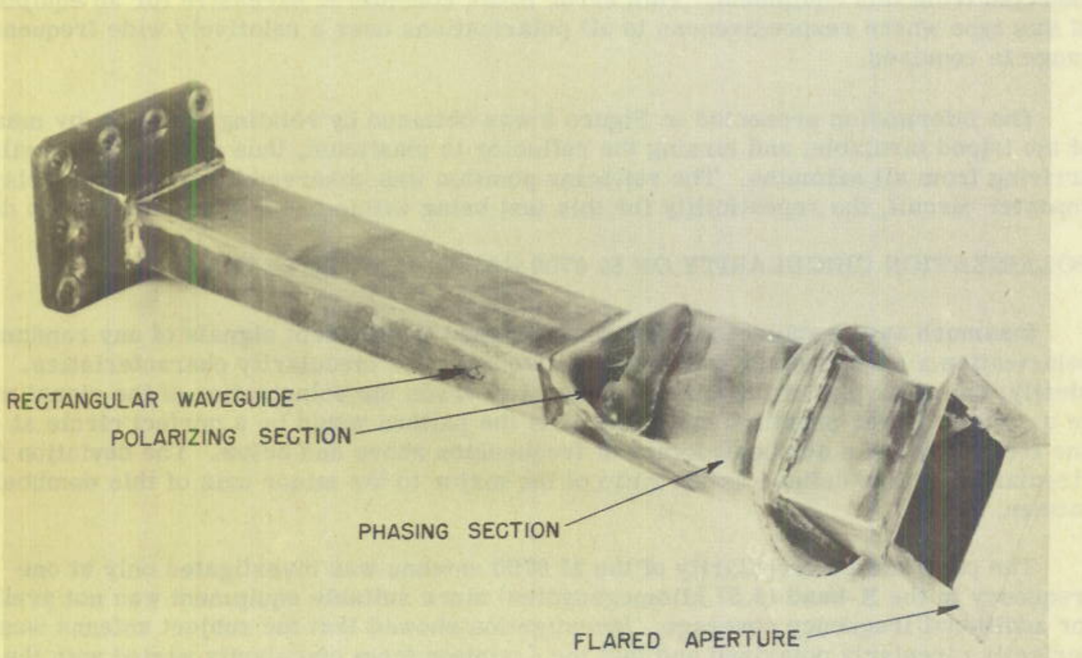

Fig. 6 - Circularly Polarized Horn

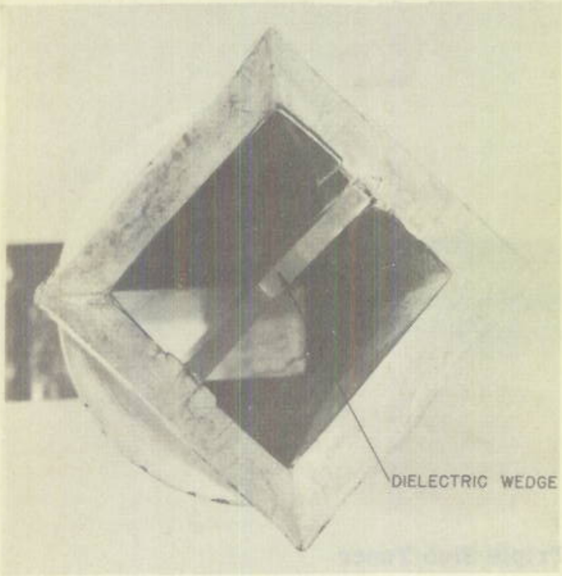

Fig. 7 - View Looking Into Mouth of Circularly Polarized Horn

connection of the antenna to the receiving equipment may be accomplished by either rigid or flexible waveguide.

INSTRUMENTAL ERROR

One of the primary considerations given to any direction finder is the question of obtaining and maintaining low instrumental error. Ordinarily, in the case of lower frequency direction finders where substantially vertically polarized waves are involved, calibration curves are utilized to correct the observed bearings. However, in the case of a circularly polarized antenna in which perfect circularity is not obtained, the instrumental error is a function of the signal polarization. Inasmuch as the operator has no means at his control to determine the signal polarization, calibration curves would have little or no meaning. Figure 8, which shows the errors for signals of four polarizations at 9.57 kilomegacycles, indicates that bearings in error by plus or minus four degrees can be expected from this equipment. This error is not considered excessive for an equipment of this type where responsiveness to all polarizations over a relatively wide frequency range is required.

The information presented in Figure 8 was obtained by rotating the horn, by means of the tripod turntable, and turning the reflector to maximum, thus simulating signals arriving from all azimuths. The reflector position was observed by means of a Selsyn repeater circuit, the repeatibility for this test being within one degree from day to day.

POLARIZATION CIRCULARITY OF M 6700 RADAR D; F. ANTENNA

Inasmuch as the subject antenna was designed to intercept signals of any random polarization a careful study was made to determine its circularity characteristics. Ideally, the polar plot of the antenna response versus the polarization of the signal would be a circle. Under practical considerations the pattern would be a perfect circle at only one frequency and a dumbbell figure at frequencies above and below. The deviation from circularity is then defined as the ratio of the major to the minor axis of this dumbbell pattern.

The polarization circularity of the M 6700 antenna was investigated only at one frequency in the X-band (9.57 kilomegacycles) since suitable equipment was not available for additional frequency coverage. Investigation showed that the subject antenna was not perfectly circularly polarized and that the deviation from circularity varied with the azimuth of signal arrival. Figure 9 shows the possible variation in relative power available to the receiver due to the direction of signal arrival and signals of all plane polarizations. The data indicates that the maximum deviation from circularity is approximately 5.8 decibles (corresponding to the power ratio of 28 to 7.4 at approximately 80 degrees on Figure 9) and the minimum deviation about 1 decibel.

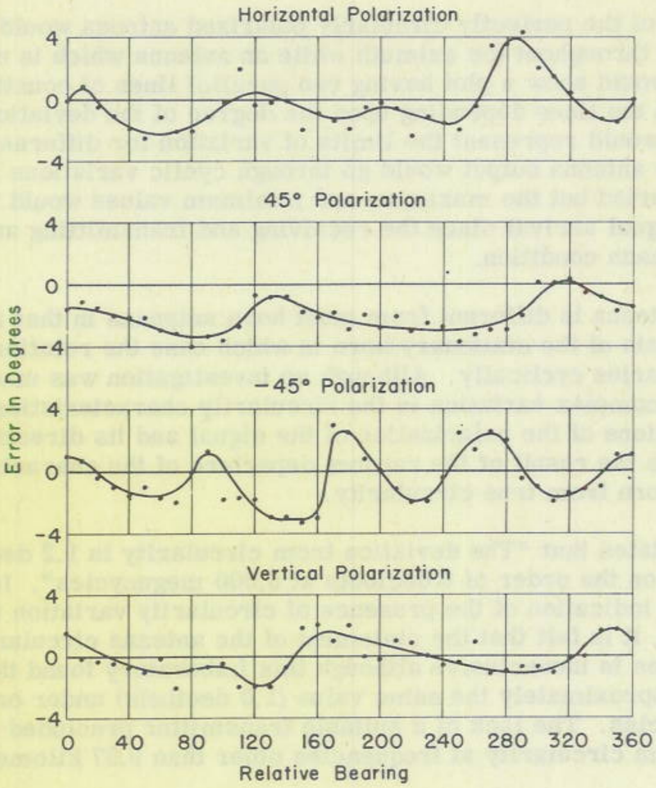

Fig. 8 - Instrumental Error of M 6700 Antenna at 9.57 Kilomegacycles

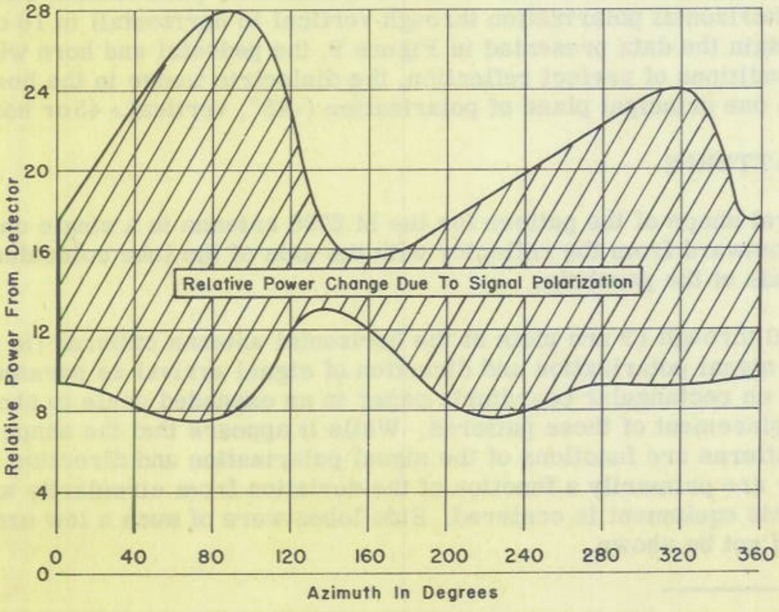

Fig. 9 - Polarization Circularity of M 6700 Antenna at 9.57 Kilomegacycles

A similar plot of the perfectly circularly polarized antenna would be a single line of constant amplitude throughout the azimuth while an antenna which is not perfectly circularly polarized would show a plot having two parallel lines of constant amplitude, the separation between the lines depending upon the degree of the deviation from circularity. The parallel lines would represent the limits of variation for different signal polarizations. In other words, the antenna output would go through cyclic variations as the signal polarization was varied but the maximum and minimum values would remain the same for all directions of signal arrival since the receiving and transmitting antennas would be normalized under each condition.

The M 6700 antenna is different from most horn antennas in that an inclined reflector rotates about the axis of the stationary horn in which case the relation between the horn and the reflector varies cyclically. Although no investigation was made to determine the reason for the complex variation in the circularity characteristics of the complete antenna with variations of the polarization of the signal and its direction arrival, it is believed that this is the result of the random departure of the characteristics of both the reflector and the horn from true circularity.

Reference 1* states that "The deviation from circularity is 1.2 decibels at 10,000 megacycles and is on the order of 6 decibels at 5,000 megacycles". Inasmuch as this reference gives no indication of the presence of circularity variation with azimuth and no test procedures, it is felt that the statement of the antenna circularity as 1.2 decibels at 10 kilomegacycles is inconclusive although this Laboratory found the deviation from circularity to be approximately the same value (1.0 decibels) under one specific condition at 9.57 kilomegacycles. The lack of a suitable transmitter precluded any determination of the deviation from circularity at frequencies other than 9.57 kilomegacycles.

To simulate signals arriving from different azimuths, the M 6700 antenna pedestal (to which the circularly polarized horn is secured) was rotated in 45 degree steps always orienting the reflector to maximum while the transmitter polarization was varied through 180 degrees (horizontal polarization through vertical to horizontal) in 10 degree increments. In order to obtain the data presented in Figure 9, the pedestal and horn were rotated such that, under conditions of perfect reflection, the dielectric wedge in the horn would correspond to one principal plane of polarization (-45°, vertical,+ 45or horizontal).

ANTENNA PATTERNS

The general shape of the pattern for the M 6700 antenna is a single unidirectional lobe pointing outward from the reflector with the axis of the lobe coincident with the plane of the axis of the parabola.

Figures 10 through 13 are plots of the horizontal antenna patterns (in the vicinity of the lobe) with signal polarization and direction of signal arrival as parameters. The data are presented on rectangular coordinate paper to an expanded scale to show better the shape and displacement of these patterns. While it appears that the shape and displacement of the patterns are functions of the signal polarization and direction of signal arrival, in reality they are primarily a function of the deviation from circularity around which the operation of this equipment is centered. Side lobes were of such a low order of magnitude that they could not be shown.

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* Confidential "Instruction Book For M 6700 X-Band D/F Antenna and Associated Components." Radio Research Laboratory, Harvard University 411-1B-43,dated 8 October 1945. Contract OEMsr-411.

Table 1 gives the beamwidths of the patterns taken at the half power points for the various test conditions. Although the horizontal beamwidths vary between 8 and 13 degrees, the average beamwidth of this equipment is approximately 11 degrees.

TABLE 1

Azimuthal Antenna Beamwidth in Degrees At The Half Power Points

Azmiuth of Source in Degrees	Signal Polarization in Degrees			
	-45	Vert.	45	Horiz.
0	10.0	8.0	11.7	13.0
45	12.8	11.3	8.7	13.0
90	8.8	10.5	12.4	9.5
135	13.0	10.2	10.2	9.8

The horizontal antenna patterns were obtained by rotating the reflector with the horn oriented in such a way as to simulate signals arriving from four azimuths, spaced at 45 degree intervals, under conditions of four signal polarizations. A Selsyn repeater circuit was used to determine the position of the reflector.

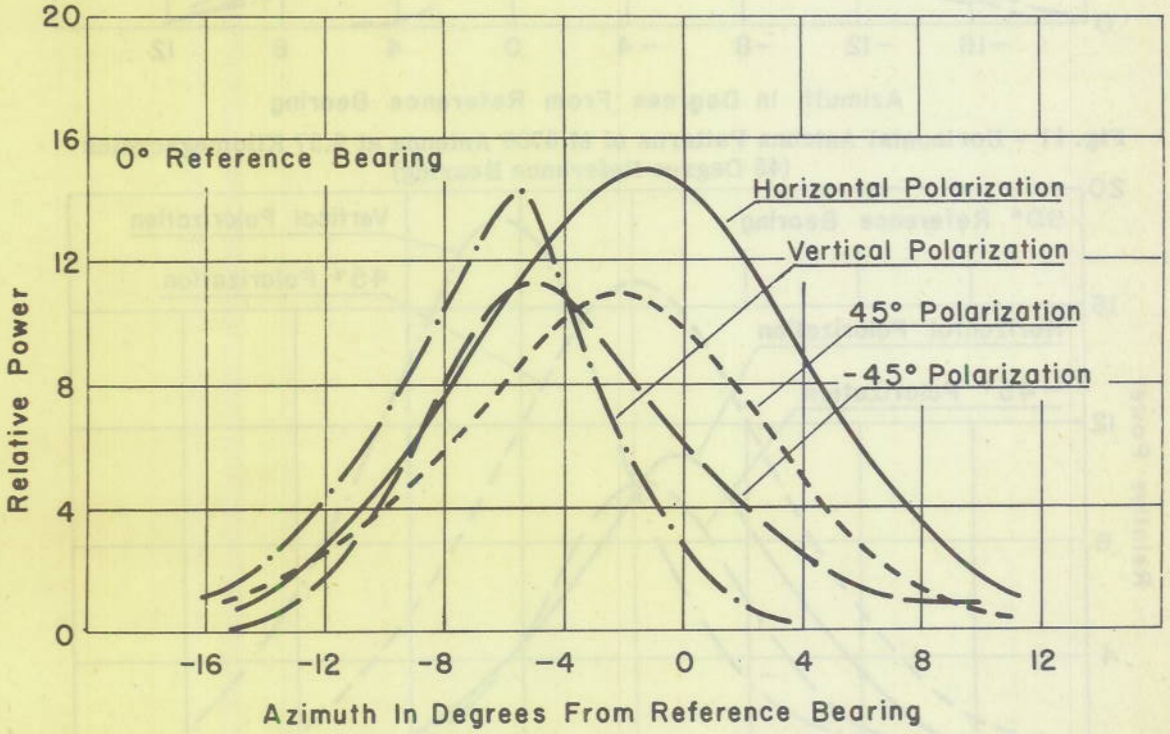

Fig. 10 - Horizontal Antenna Patterns of M 6700 Antenna at 9.57 Kilomegacycles (0 Degree Reference Bearing)

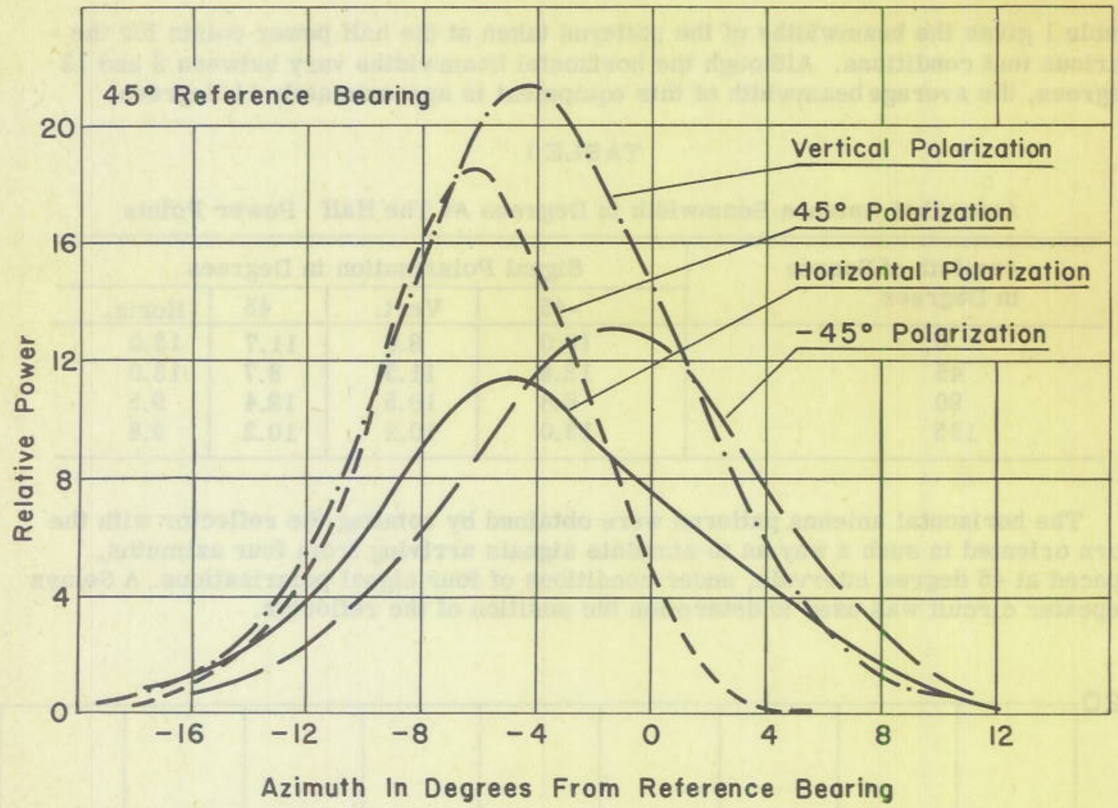

Fig. 11 - Horizontal Antenna Patterns of M 6700 Antenna at 9.57 Kilomegacycles
(45 Degree Reference Bearing)

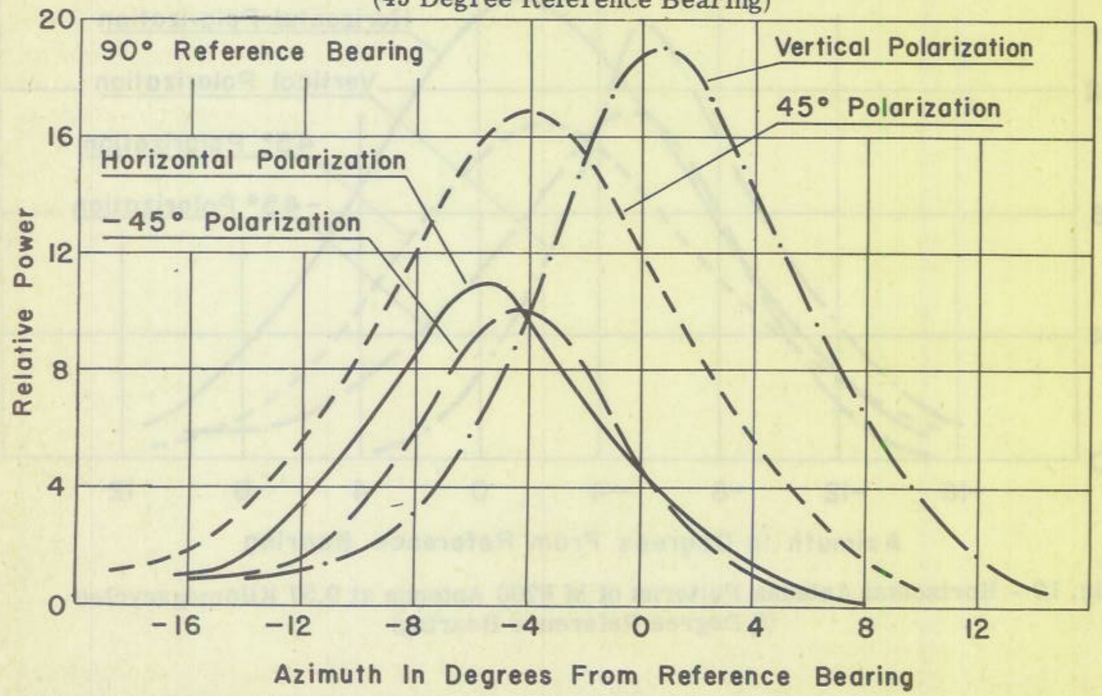

Fig. 12 - Horizontal Antenna Patterns of M 6700 Antenna at 9.57 Kilomegacycles
(90 Degree Reference Bearing)

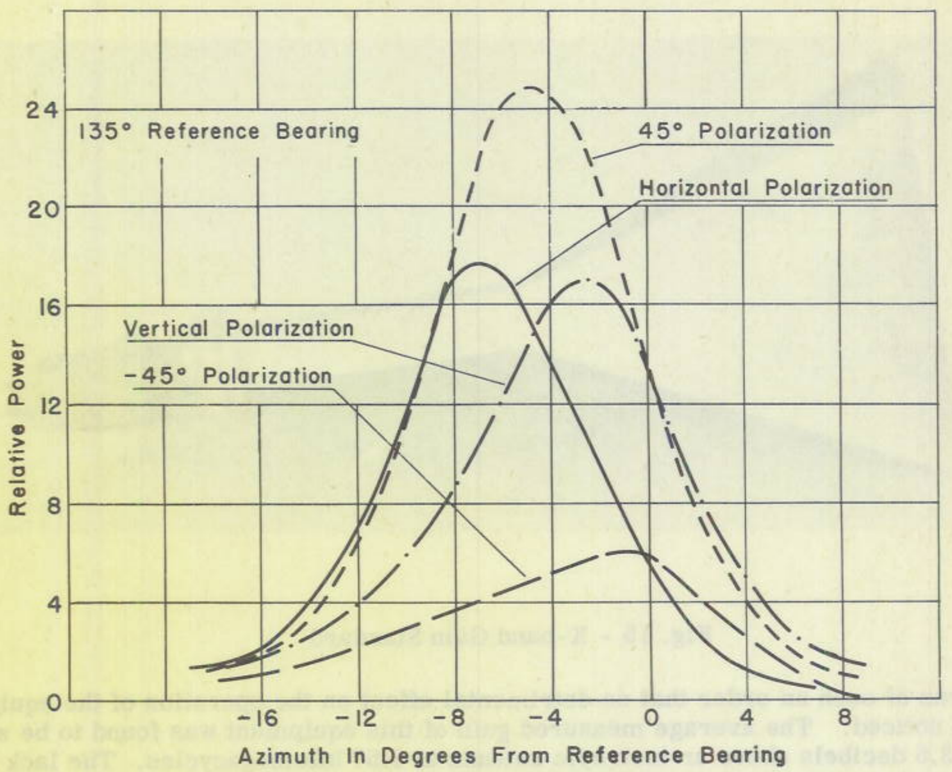

Fig. 13 - Horizontal Antenna Patterns of M 6700 Antenna at 9.57 Kilomegacycles (135 Degree Reference Bearing)

The vertical antenna pattern is shown in polar form in Figure 14. This pattern, which was taken under the condition of a vertically polarized signal arriving from an azimuth of zero degrees is seen to be considerably broader than the horizontal patterns. This pattern was taken by tilting the subject antenna in the vertical plane by means of the tripod arrangement.

ANTENNA GAIN

The gain of any antenna system is a function of its size, number of antenna elements, the frequency and the percentage frequency coverage. The subject antenna cannot be expected to have a gain which is comparable to the gains obtained in other microwave antennas because of the wide frequency coverage required.

Inasmuch as previous tests indicated that the shape of the antenna patterns and deviation from circularity were functions of the direction of signal arrival and the signal polarization, tests were conducted to determine the effect of these parameters on the gain. The results of this investigation showed that, while the gain was affected by these parameters, the variation

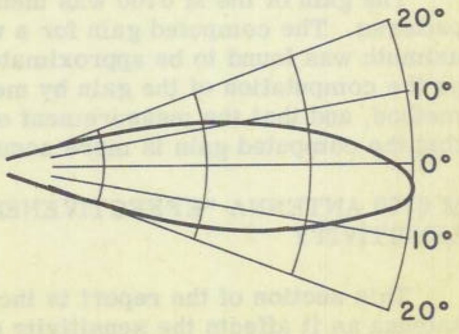

Fig. 14 - Vertical Antenna Pattern of M 6700 Antenna at 9.57 Kilomegacycles

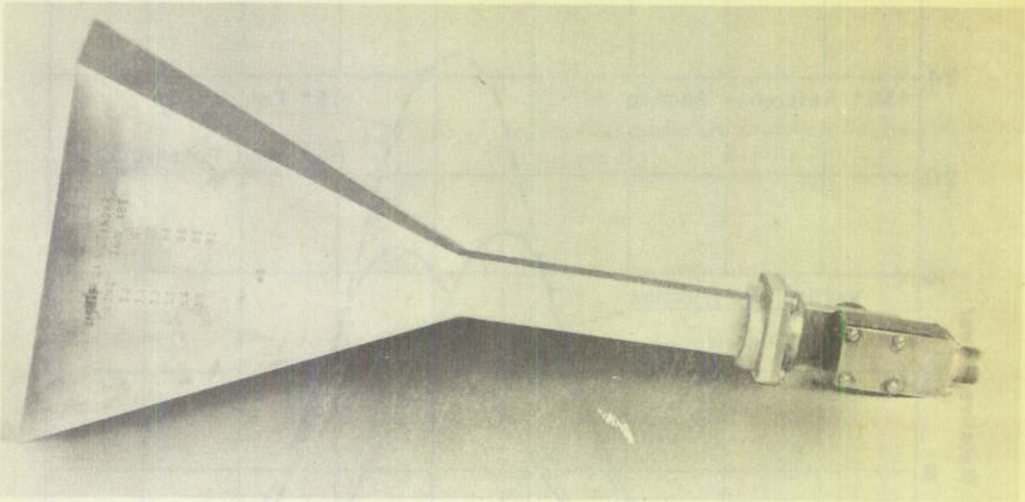

Fig. 15 - X-band Gain Standard

in gain was of such an order that no detrimental effect on the operation of the equipment would be noticed. The average measured gain of this equipment was found to be approximately 13.5 decibels above an isotropic antenna at 9.57 kilomegacycles. The lack of suitable equipment precluded the determination of the gain at other frequencies. The radome was found to offer approximately 1 decibel attenuation to the signal at the same test frequency.

A calibrated gain standard horn was used in these tests to measure the gain of the M 6700 antenna at this test frequency in the X-band. This gain standard had an aperture of 29 square inches and a gain of 19.5 decibels above an isotropic antenna at this frequency. Figure 15 is a photograph of this gain standard. The outputs of the M 6700 and the gain standard were compared for each test condition from which the gain of the subject antenna was then readily obtained.

The gain of the M 6700 was then computed from the horizontal and vertical antenna patterns. The computed gain for a vertically polarized signal arriving from zero degree azimuth was found to be approximately 15.6 decibels above an isotropic antenna. Inasmuch as the computation of the gain by means of the antenna patterns is the more fundamental method, and that the measurement of the gain assumes perfect antenna match, it is felt that the computed gain is more accurate although the discrepancy is quite small.

M 6700 ANTENNA "EFFECTIVENESS" AND PROBABLE DIRECTION FINDER SENSITIVITY

This section of the report is included to point out the limitations of the subject antenna as it affects the sensitivity of a complete direction finder equipment. Although, at the present time, equipment in the microwave range is not considered as to its sensitivity, it is felt that this information is very desirable for direction finders and a brief discussion of probable sensitivities is thus included in this report. Inasmuch as the sensitivity of a direction finder is a function of the "effectiveness" of the antenna and the sensitivity of the receiver, the discussion can only be concerned with the "effectiveness" of the M 6700 antenna as used with either the theoretically perfect receiver or existing receivers such as the AN/APR-5A with a separate crystal mixer stage for X-band reception.

The "effectiveness" of an antenna is defined in Reference 2[†] as "that quantity which when multiplied by the field intensity yields the voltage across the load impedance" This quantity can be readily determined for a matched antenna from the effective height. The effective height of a half wave dipole at 9.57 kilomegacycles is one centimeter. Inasmuch as the gain of the M 6700 antenna is approximately 15.6 decibels above an isotropic antenna, or 13.46 decibels above a half wave dipole, (the gain of a half wave dipole being 2.14 decibels above an isotropic antenna), the effective height of the M 6700 is 4.7 centimeters. The term "effective height" of an antenna has little or nor practical value for most antennas, the tuned loop being an exception, in that it is defined for open circuit conditions. When the antenna is matched, it is well known that only one half the voltage induced in the antenna will be present across the load impedance, the other half being accounted for by the internal impedance of the antenna. It is this useful condition of antenna match for which the term "effectiveness" is given. Therefore, the "effectiveness" of a matched antenna is one half the effective height, or 2.35 centimeters for the M 6700 antenna. In order to utilize this information to evaluate the probable direction finder sensitivity, the sensitivity of existing receivers must be known.

The theoretical limit of sensitivity for a receiver, such as an AN/APR-5A, having a 10 megacycle bandwidth and an input impedance of 50 ohms is 30 microvolts for a 20 decibel signal plus noise to noise ratio. Present day receivers, in the frequency range of interest in this problem, have a noise factor of 18.5 decibels. The sensitivity of present receivers, therefore, is of the order of 250 microvolts for a 10 megacycle bandwidth.

The antenna "effectiveness" and the receiver sensitivity can then be combined to give probable direction finder sensitivities. For a receiver having a 10 megacycle bandwidth, the direction finder would require a field intensity of approximately 10,640 microvolts per meter to obtain a 20 decibel signal plus noise to noise ratio. With the theoretically perfect receiver, the field intensity required would be only about 1280 microvolts per meter. It should be stated, however, that bearings of a fair degree of accuracy can be obtained on signals with a one to one signal plus noise to noise ratio which would then mean that the field intensity would need be only one tenth of that required for a 20 decibel signal plus noise to noise ratio.

CIRCULARLY POLARIZED HORN PATTERNS

Patterns were taken of the circularly polarized horn at several frequencies throughout the band to examine the possibility of any major side lobes or a sharp change in the shape of the patterns. Figures 16 through 20 give these patterns for both horizontally and vertically polarized signals.

The variation in the amplitudes of the patterns for vertically and horizontally polarized signals is due to the deviation from circularity of the horn. Although no patterns were obtained above 10.3 kilomegacycles, the general shapes below this frequency are such that a decided change in the way of major side lobes is not probable.

[†] NRL Confidential Report R-2742, "Test of RCA UHF Direction Finder Developed Under NDRC Contract OEMsr-1009" by K. O. Hornberg.

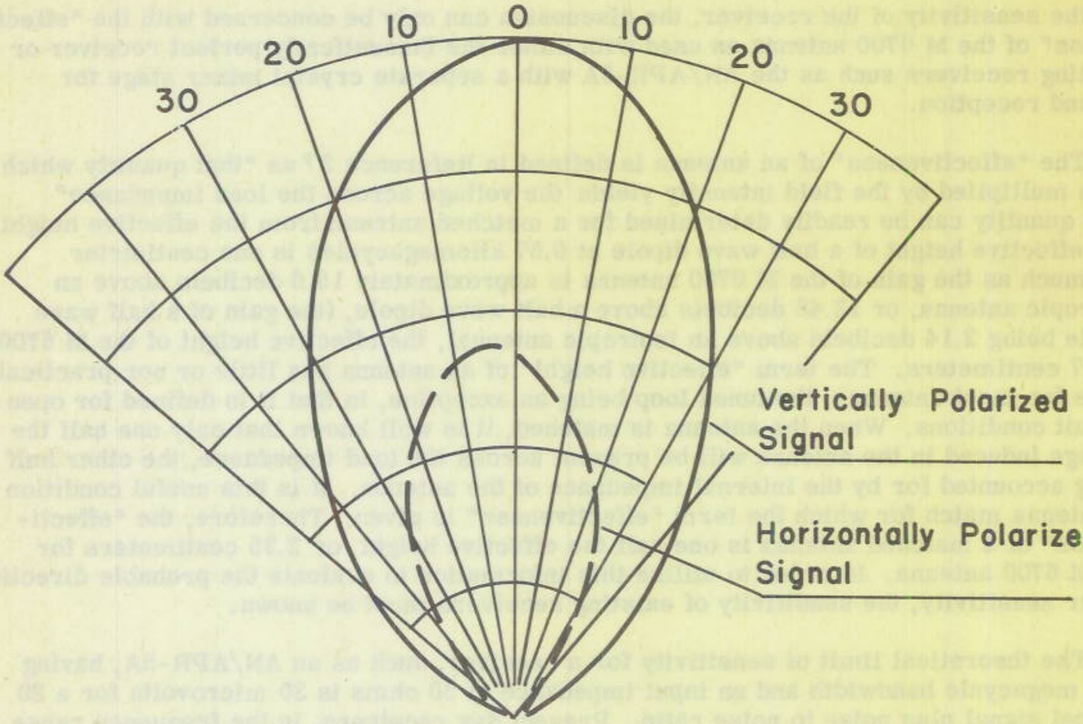

Fig. 16 - Horn Patterns at 5.4 Kilomegacycles

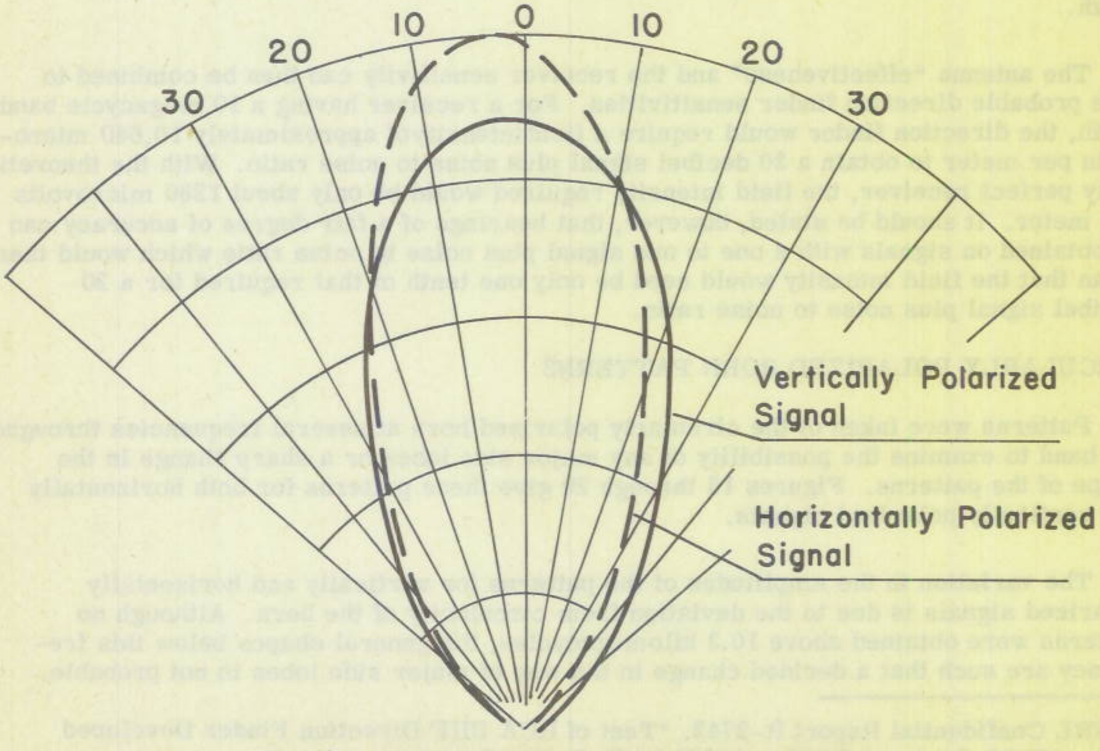

Fig. 17 - Horn Patterns at 7.6 Kilomegacycles

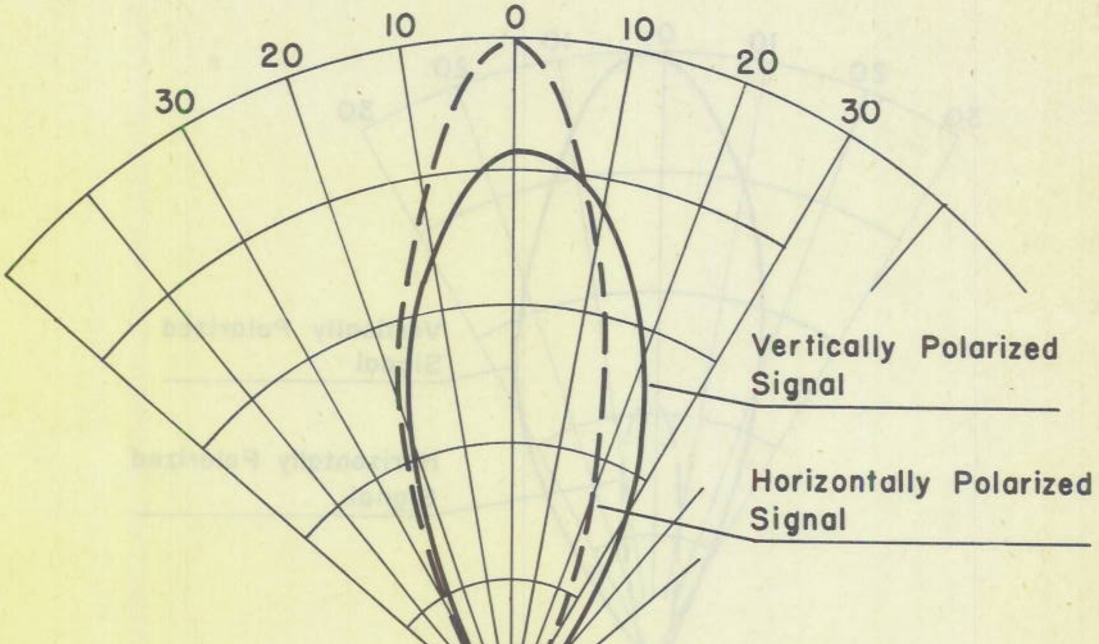

Fig. 18 - Horn Patterns at 9.1 Kilomegacycles

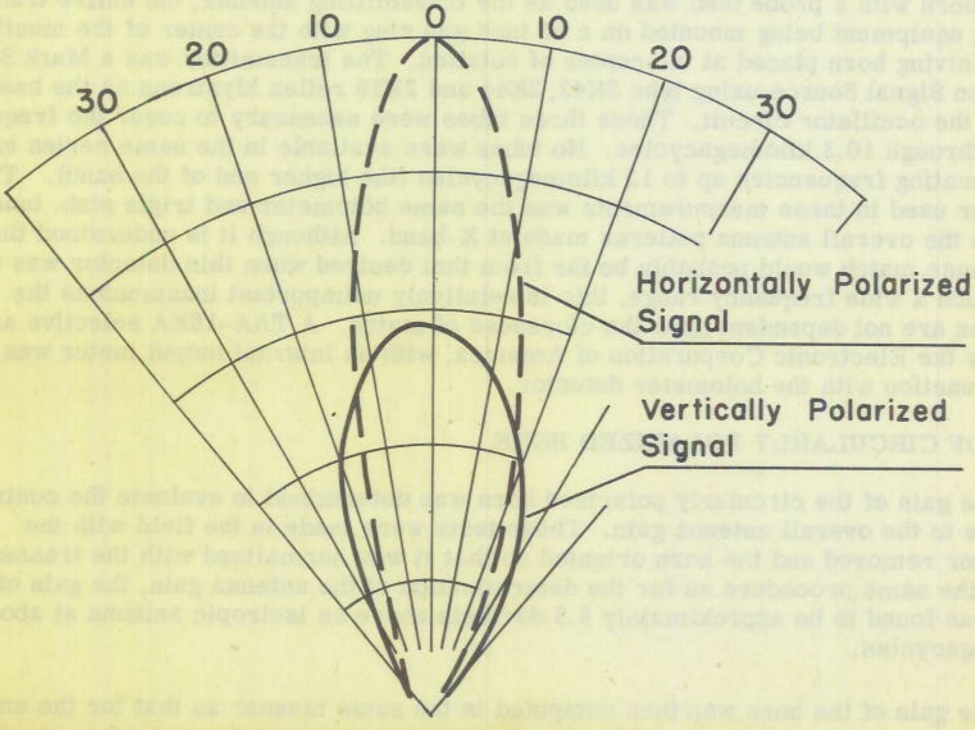

Fig. 19 - Horn Patterns at 9.7 Kilomegacycles

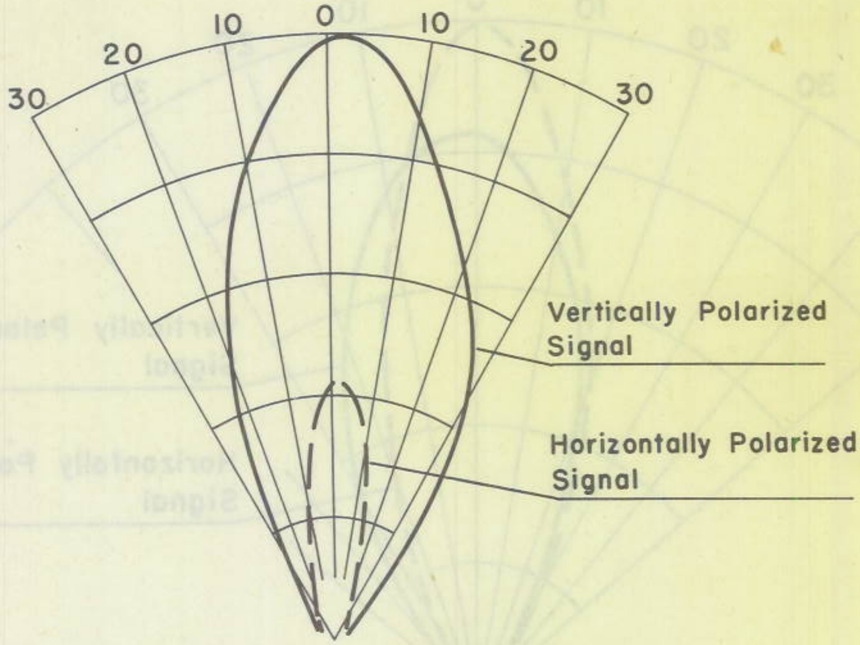

Fig. 20 - Horn Patterns at 10.3 Kilomegacycles

The test setup shown in Figures 21 and 22 was used to obtain these horn patterns. The horn was mounted so that the dielectric wedge was in the horizontal plane. A small flared horn with a probe feed was used as the transmitting antenna, the entire transmitting equipment being mounted on a 30 inch gun ring with the center of the mouth of the receiving horn placed at the center of rotation. The transmitter was a Mark SX-12 Klystron Signal Source using type 2K43, 2K44 and 2K39 reflex klystrons as the basic unit of the oscillator circuit. These three tubes were necessary to cover the frequency range through 10.3 kilomegacycles. No tubes were available in the same series capable of generating frequencies up to 12 kilomegacycles (the higher end of the band). The detector used in these measurements was the same bolometer and triple stub tuner as used in the overall antenna patterns made at X-band. Although it is understood that the impedance match would probably be far from that desired when this detector was used over such a wide frequency range, this is relatively unimportant inasmuch as the patterns are not dependent upon the closeness of match. A TAA-16EA selective amplifier, built by the Electronic Corporation of America, with an internal output meter was used in conjunction with the bolometer detector.

GAIN OF CIRCULARLY POLARIZED HORN

The gain of the circularly polarized horn was determined to evaluate the contribution it made to the overall antenna gain. These tests were made in the field with the reflector removed and the horn oriented so that it was normalized with the transmitter. Using the sâme procedure as for the determination of the antenna gain, the gain of the horn was found to be approximately 6.8 decibels above an isotropic antenna at about 9.57 kilomegacycles.

The gain of the horn was then computed in the same manner as that for the antenna and was found to be 9.9 decibels above an isotropic antenna at the same frequency. The discrepancy between the measured and the computed gains can be attributed to two factors.

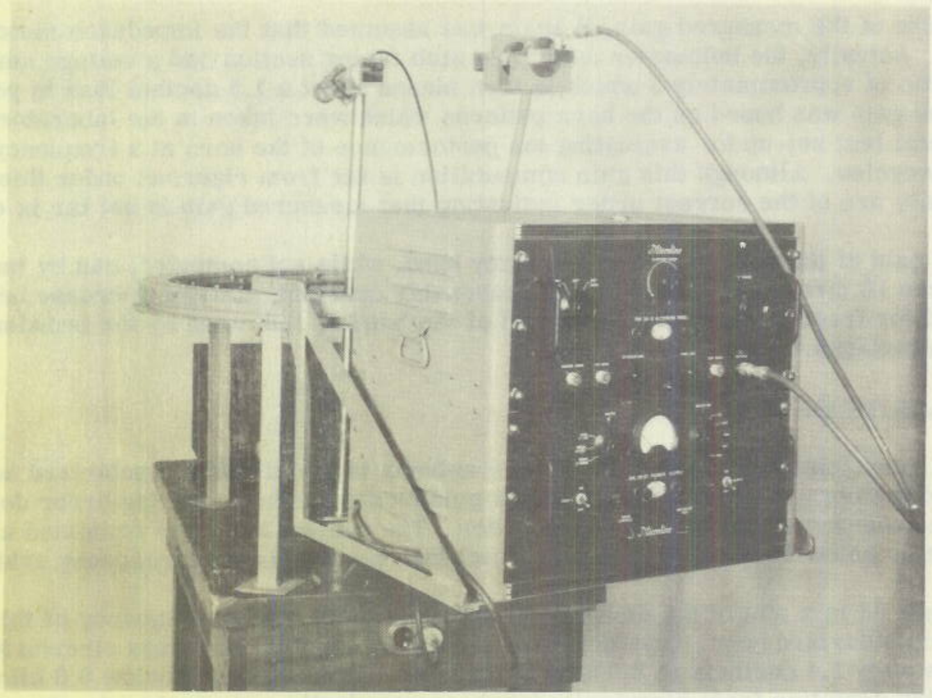

Fig. 21 - Laboratory Setup For Horn Evaluation Showing Signal Source

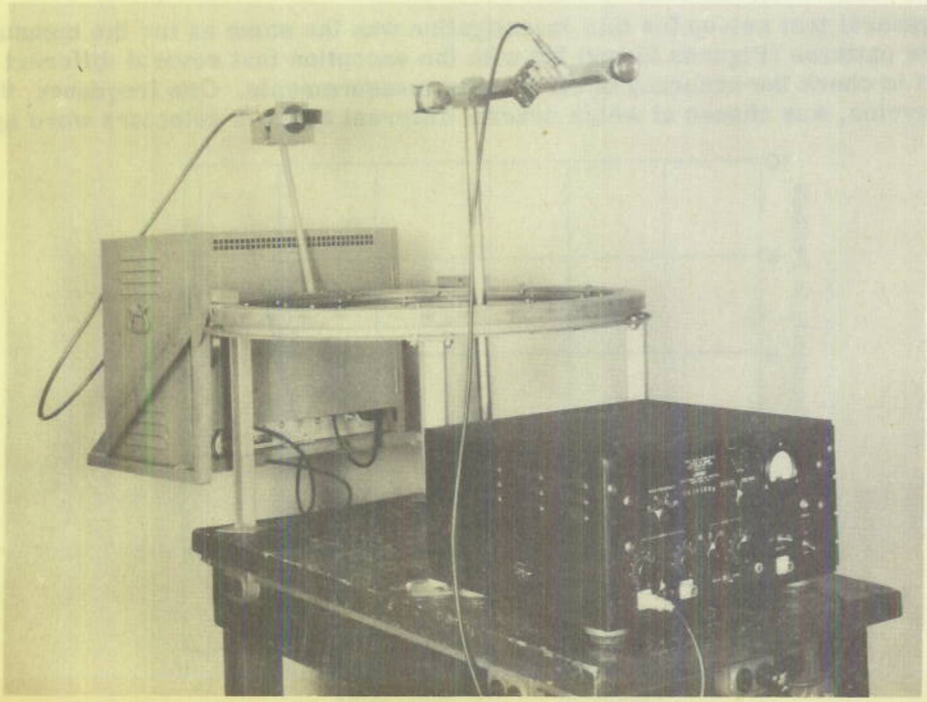

Fig. 22 - Laboratory Setup For Horn Evaluation Showing Receiving Equipment

In the case of the measured gain, it again was assumed that the impedance matching was perfect. Actually, the bolometer and triple stub tuning section had a voltage standing wave ratio of approximately 3 which in turn means about a 1.5 decibel loss in power. The computed gain was based on the horn patterns which were taken in the laboratory using the special test set-up for evaluating the performance of the horn at a frequency of 9.7 kilomegacycles. Although this gain computation is far from rigorous under this condition, the results are of the correct order indicating that measured gain is not far in error.

The gain of the horn over the frequency band, while not computed, can by inspection of Figures 16 through 20 be said to be reasonably constant, a slight decrease being expected for frequencies at the lower end of the band as indicated by the broadening of the horn patterns.

CIRCULARITY OF HORN

The most important unit of the M 6700 antenna is the circularly polarized horn. The ability of the horn to accept signals of any polarization without bearing error depends upon the accuracy of design and construction. The subject horn was examined at several frequencies below 10.3 kilomegacycles which was the top limit in frequency available.

Figure 23 is a plot of the deviation from circularity against frequency of this circularly polarized horn. It is seen that the minimum deviation from circularity is approximately 1.4 decibels at 9.0 kilomegacycles. At frequencies below 9.0 kilomegacycles, the deviation from circularity increases gradually and reaches a value of approximately 4.9 decibels at 5.4 kilomegacycles. Above 9.0 kilomegacycles, the deviation from circularity increases rapidly, a value of 8.4 decibels being recorded at 10.3 kilomegacycles.

The general test set-up for this investigation was the same as for the measurement of the horn patterns (Figures 21 and 22) with the exception that several different detectors were used to check the accuracy of circularity measurements. One frequency, 9.56 kilomegacycles, was chosen at which several different types of detectors were applicable

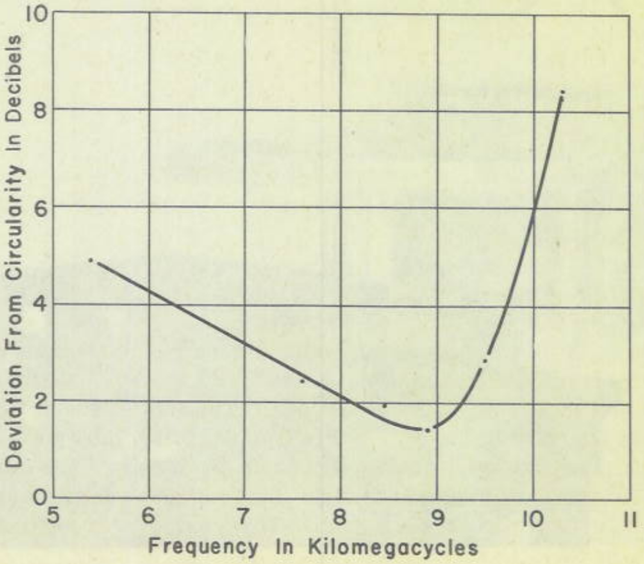

Fig. 23 - Circularity of Horn

and a very careful examination made. These detectors included: (a) the bolometer, triple stub tuner and the TAA-16EA amplifier used in the majority of the tests; (b) the bolometer, triple stub tuner as a termination to a slotted waveguide in which a probe was inserted, the output from the probe being fed into an X-band TSX-4SE spectrum analyzer; (c) an X-band probe termination with a reducing section, the output of the probe also being fed to the spectrum analyzer; and (d) a Sperry Microline Barretter Mount type 82X with the reducing section, the output of this detector being fed to the amplifier used with the regular bolometer detector. This reducing section was necessary because the Barretter Mount and the X-band probe termination had different size waveguides than the circularly polarized horn.

The results of this investigation gave circularities which were within approximately 1 decibel indicating that the type of detector played no part in the actual values of circularity obtained.

Circularity data were obtained by normalizing the receiving and transmitting horns and rotating the transmitting horn on its axis through 360 degrees. A minimum of three circularity ratios were taken for each frequency investigated, the average of these readings being shown on the curve (Figure 23).

FLIGHT TEST OF M 6700 RADAR D. F. ANTENNA

The purpose of this test was to determine the maximum range that a Model DBM-1 Direction Finder equipped with the subject antenna would be capable of bearing determination on an airborne X-band radar. A secondary result desired from this test was the bearing or tracking accuracy.

Inasmuch as flight tests were not permitted over the Washington area, the equipment was transported to the U. S. Naval Air Test Center at Patuxent River, Maryland where the target plane was based. The M 6700 antenna was mounted on the roof of a jeep-drawn trailer with the receiving equipment and DBM-1 indicator inside. A gasoline-engine-driven generator was mounted in the rear of a jeep so that the equipment was a complete unit by itself and could be put into operation in a few minutes with no external facilities necessary. Figures 24 through 28 are photographs of the installation at Patuxent River. In order to reduce the noise caused by the power source, it was necessary to utilize noise filters, better bonding between the units, and shielding of the antenna motor power cable.

The target plane used in this test was a Navy type SNB-1 equipped with an AN/APS-4 X-band radar mounted under the fuselage. To facilitate the tests, the entire radar was remounted so that it faced aft.

The AN/APS-4 equipment is a search type radar operating in the X-band. The transmitter-receiver unit is contained in a pressurized structure about 61 inches long and 17 inches in diameter. This structure has a plastic hemispherical nose and a conical tail to provide stream-lining. Figure 26 is a photograph showing the AN/APS-4 mounted for these tests. The antenna consists of a feed horn mounted at the end of a section of waveguide and equipped with a parabolic reflector (approximately 12 inches in diameter). The antenna scans the azimuth at a nominal rate of 30 oscillations per minute. Other nominal characteristics of this radar include a pulse repetition frequency of 1000 cycles per second with a 6 microsecond pulse length. The peak power of this equipment is approximately 35 kilowatts.

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Fig. 24 - Flight Test Installation at Patuxent River, Md.

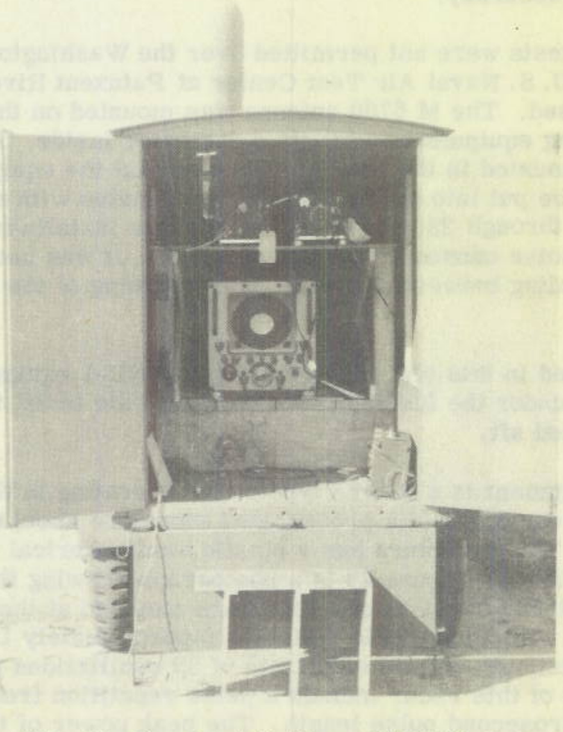

Fig. 25 - Trailer Installation of M 6700 Antenna and Associated Receiving Equipment

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Fig. 26 - Target Plane With AN/APS-4 Radar Mounted Facing Aft

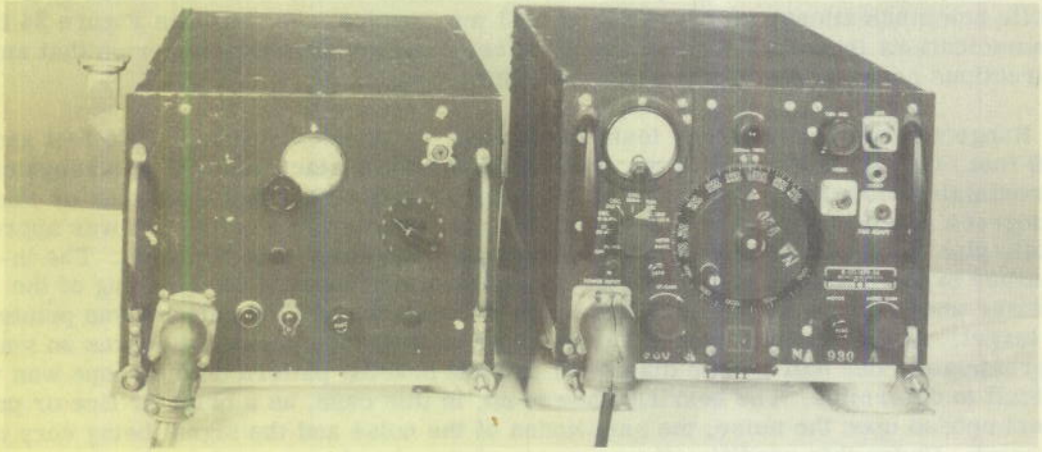

Fig. 27 - X-band Mixer and R-111/APR-5A Receiver

Fig. 28 - Power Supply Installed in Jeep

In the two-line scan as used for searching and mapping of surface targets, each scanning cycle consists of two horizontal sweeps, one at the tilt control setting and the other four degrees below it. These sweeps scan an elliptical area 10 degrees in elevation (four degrees between beam centers plus six degrees of beam width) by 150 degrees in azimuth. The rate of scan is about 30 two-line frames per minute.

The receiving equipment as furnished with the M 6700 antenna was used for the flight tests. Although this receiver was not subjected to any performance tests, a brief description of it is included for reference. In order to receive signals in the X-band, a separate mixer unit is used together with the intermediate frequency stages and succeeding stages of an R-111/APR-5A receiver. The mixer as used for the reception of signals in the X-band employs a Western Electric 723A/B reflex klystron (Shepherd-Pierce tube) as an oscillator with an untuned mixer stage giving an intermediate frequency of 30 megacycles. Inasmuch as two controls (cavity and reflector voltage) are necessary to operate the klystron, the "tuning" of the receiver is quite difficult.

Communication between the plane and the direction finder was facilitated by a mobile communications unit operating at 6.63 megacycles. As shown in Figure 24 this communications truck was located about 50 feet from the direction finder so that any instructions could be readily transmitted to the plane.

Range and bearing accuracy tests were made for plane altitudes of 1000 feet and 5000 feet. On the first run with the plane at 1000 feet, contact was lost at a range of approximately 40 miles. For the first 10 miles or so the bearings were plus or minus 15 degrees of correct bearing after which the accuracy became better and was approximately plus or minus 5 degrees maximum at ranges greater than 20 miles. The inaccuracy of the bearings at the shorter ranges was attributed to the blocking of the receiver under strong signal conditions present when the M 6700 antenna was pointed at the target. At the extreme range, the diameter of the scope presentation was so small (approximately one half inch in diameter) that the bearing pattern on the scope was very difficult to determine. The bearing showed up, in this case, as a brighter line or pattern superimposed upon the noise, the amplitudes of the noise and the signal being very nearly the same. Under this condition the presence of the signal was much easier determined by auditory means than by scope presentation. The plane lost contact with the direction finder area by means of its radar at a range of approximately 30 to 35 miles. This range of radar contact may be questionable due to the fact that the radar operator was inexperienced.

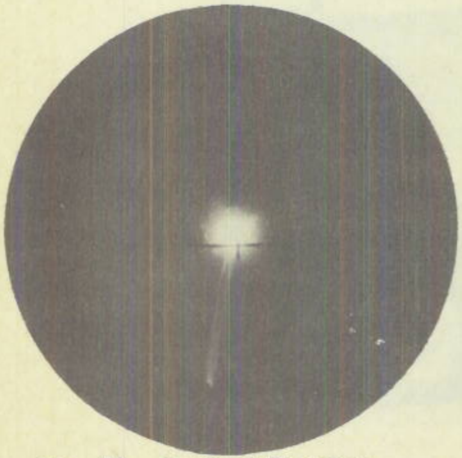

Fig. 29 - Typical Bearing Pattern at X-band

The maximum range of direction finder contact was increased to approximately 65 miles when the plane flew the same course at an altitude of 5000 feet. The accuracy of the bearings for this test was almost identical with that for the 1000 foot test. For some reason, the maximum radar contact range for this test was not observed and cannot be given.

It was found that the best intercept was obtained when the M 6700 reflector was rotated at its minimum speed, approximately 2 r.p.m. At this very slow rate of rotation the signals appeared as sharp lines on the indicator, while at higher rotational speeds the patterns became broader and the frequency of intercept greatly reduced. Figure 29 is a photograph of a typical bearing pattern.

The mobile communication equipment, when transmitting, had a detrimental effect upon the conduct of these tests inasmuch as a harmonic of the signal frequency was so strong as to enter the direction finder through the receiver intermediate frequency stages and be visible on the indicator as well as audible through the earphones. This reception of the communication signal showed up very bright on the indicator and completely covered the working area of the scope, blocking out the desired signal. It was thus necessary to reduce the transmission of instructions to the plane considerably, particularly at the extreme ranges in order that an erroneous loss of direction finder contact would not result. These instructions consisted primarily of asking for the plane's range. This method of determining range was found to be more suitable than any other method such as time synchronization with the plane noting distance with respect to time.

STANDING WAVE RATIO OF THE M 6700 RADAR D. F. ANTENNA

The measurement of standing wave ratios for circularly polarized antennas, such as the M 6700, presents a question as to their actual meaning. This question arises from the fact that M 6700 antenna is primarily intended for the reception of plane polarized waves, but that in the measurement of standing wave ratios the horn is employed as a transmitting antenna and is driven by signal generating source, the field produced at the mouth of the horn being circularly polarized. Inasmuch as the same field condition can not be obtained during the measurement of the standing wave ratios as exists in normal operation, these measurements have no meaning.

Although standing wave ratios have been used in the ultra high and very high frequency ranges to indicate some measure of antenna efficiency, it has been the practice to associate microwave antenna efficiency with its gain rather than its standing wave ratio. A discussion of the gain of the M 6700 is given in a previous paragraph.

M 6700 ANTENNA WAVEGUIDE ANALYSIS

The wide frequency coverage of this equipment indicated that an analysis of the waveguide as to its suitability was adviseable. In order to cover this frequency range, the M 6700 utilizes 3/4 inch by $1\frac{1}{2}$ inch nominal size waveguide. The cutoff frequency for this size waveguide was found to be approximately 4.3 kilomegacycles from formulas given in Reference 3 ‡ which makes the waveguide satisfactory in this respect.

The attenuation in rigid copper waveguide is approximately 0.035 decibels per foot, while rigid brass waveguide has approximately twice the attenuation as that of copper. The best flexible waveguide, which is made of silver plated copper, has an attenuation of approximately 0.087 decibels per foot. Loosely wound flexible aluminum waveguide has an attenuation between 1.5 and 4 decibels per foot depending on the looseness of winding.

In order to obtain the maximum efficiency from the coupling system, it is therefore seen that a minimum amount of flexible waveguide should be used and that the rigid waveguide should be of copper.

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‡ Microwave Transmission Design Data. Sperry Gyroscope Company, Inc. Confidential Publication No. 23-80.

CONCLUSIONS

It is concluded:

A. That the M 6700 Radar D. F. Antenna furnished the Laboratory was not a prototype but merely an experimental model of a contemplated spinner for use with the Model DBM and DBM-1 radio and radar direction finders.

B. That the equipment was entirely suitable for evaluation of its operating characteristics and for use to form general specifications for production models.

C. That, inasmuch as this equipment was not a prototype of a production model, type tests were not performed to determine the mechanical suitability although a mechanical inspection was made to determine any obvious flaws.

D. That the antenna is electrically suitable for duplication in its present form with the exception of the antenna reflector drive motor which should be replaced in production by some type of induction motor to eliminate troublesome commutator noise present in the existing equipment. Considerable additional development would be necessary to improve, only slightly, the present electrical characteristics.

E. That the equipment is very well mechanically designed and constructed for an experimental model, and consequently suitable for duplication with the exception of the reflector (where better fabricating techniques are recommended) and the method of support for the circularly polarized horn.

F. That satisfactory bearing determination against an airborne radar (AN/APS-4) could be made up to line of sight distances when the subject antenna was used with an insensitive receiver.

G. That while bearing errors of plus or minus four degrees can be expected for this equipment at 9.57 kilomegacycles, such errors are not considered excessive for this type antenna. Bearing errors may be slightly higher at frequencies above 9.57 kilomegacycles inasmuch as the horn has the greatest deviation from circularity at these frequencies. The lack of suitable equipment precluded the determination of bearing errors at frequencies other than 9.57 kilomegacycles.

H. That the design of the circularly polarized horn is satisfactory, the deviation from circularity being within reasonable limits considering the wide frequency range covered.

I. That while a limited number of tests were performed on this equipment, the results indicate satisfactory operation over the frequency hand of 5 kilomegacycles to 12 kilomegacycles.

RECOMMENDATIONS

It is recommended:

A. That any production models of this experimental direction finder have electrical characteristics comparable to those reported herein, and follow the same general construction as the experimental model with due regard to Naval specifications.

B. That the universal motor driving the antenna reflector in the experimental equipment be replaced in production models by some type of induction motor to eliminate commutator noise.

C. That, in order to obtain maximum coupling efficiency between the antenna and the receiving equipment, rigid copper waveguide or if possible, rigid silver plated copper waveguide be used with a minimum of flexible waveguide.

D. That the antenna reflector be mechanically redesigned to utilize better fabricating techniques.

E. That the circularly polarized horn be secured at the bottom of the antenna pedestal and held at the top by a running fit together with proper gasketing for damping purposes.

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APPENDIX

Theory of Circularly Polarized Horn

Although a rigorous explanation covering the theory of operation of the circularly polarized horn is beyond the scope of this problem, a simplified treatment can be given which for most practical purposes will suffice.

Consider the general case in which a plane polarized wave enters the mouth of the horn so that the plane of polarization is neither parallel nor perpendicular to any side of the horn. The electric vector of the incident field can be mathematically resolved into two components, one component being parallel to the dielectric wedge while the other component is perpendicular to the wedge. At the mouth of the horn, the electric vector of the incident field can be mathematically considered as two perpendicular vectors whose amplitudes are proportional to the angle of signal polarization and varying in time phase. In order to follow more clearly the action of these two vectors the vector which is perpendicular to the wedge is designated "A" and the vector which is parallel to the wedge as "B". As both of these vectors propagate down the horn, the vector B "sees" more of the wedge and is delayed because of the lower velocity of propagation in the dielectric. Inasmuch as this dielectric wedge is designed to delay the wave represented by vector "B" a quarter wavelength at one frequency, the two vectors "A'' and "B" will be in time quadrature at the far end of the wedge.

Although continuing to follow the action of the individual vectors A and B, it is interesting to note that at the far end of the wedge the condition of an elliptically polarized field is satisfied by the time and space quadrature relations of the two vectors. Special conditions of elliptically polarized fields such as circular polarization or plane polarization arise from special conditions of incidence of the original field. An incident field whose electric vector is 45 degrees to the dielectric wedge will resolve into two equal components such that at the end of the phasing section, a circularly polarized field will result. A field whose electric vector is either parallel or perpendicular to the dielectric wedge will not resolve into two components and consequently only a plane polarized field will result at the point of interest in the horn. These two special conditions are merely introduced at this point in the general discussion and are elaborated upon in later sections.

Returning to the general case and examine the polarizing or transforming section which reduces the square waveguide to a rectangular waveguide, with the dielectric wedge mounted at a 45 degree angle to the TE_{10} or principal mode of the rectangular waveguide, this polarizing section is shaped such that it resolves vector A into two components and vector B into two components in such a way that one component of A will be in space phase with one component of B but in time quadrature. These two components of A and B will add together vectorially, due to the time quadrature relation, to give a resultant vector C, which is parallel to the TE_{10} mode in the rectangular waveguide, the amplitude of which is .707 of the original field intensity. The other components of A and B also combine to give a resultant D, of the same amplitude but

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perpendicular to the TE_{10} mode. Inasmuch as energy is proportional to the square of the field intensity, each of these resultants, C and D, represents one-half the energy contained in the original impinging field. Only the energy which has its electric vector parallel to the TE_{10} mode will propagate down the waveguide, the other energy being reflected and lost. Consequently, this and any other circularly polarized horn of the same type will utilize only one-half the energy available at the mouth of the horn when used as a receiving antenna.

In a special case, mentioned previously, in which the electric vector of the impinging field makes a 45 degree angle with the dielectric wedge, at the mouth of the horn, the impinging electric vector can be mathematically considered to be resolved into two equal components, each .707 of the original vector. The action through the phasing section is identical to the general case but at the end of this section the vectors A and B are now of equal amplitude in contrast to the general case. Inasmuch as A and B are of equal amplitude and also in time and space quadrature, the condition of a circularly polarized field is satisfied. However, in order to follow through the action as in the general case the individual vectors will be dealt with rather than the field. As each vector A and B enters the polarizing or transforming section, it in turn is resolved into two components, the amplitude of each component being .707A or .707B, as the case may be, or .5 of the original electric vector. One component of each A and B is now parallel to the TE_{10} mode in the rectangular waveguide, the other components of A and B being perpendicular with the components of A and B which are in time quadrature. The components parallel to the TE_{10} mode add together vectorially to give a resultant, C, whose amplitude is equal to A or .707 of the original electric vector. In a similar manner the components of A and B which are perpendicular to the TE_{10} mode combine to give a resultant, D, also equal to .707 of the original electric vector. Thus, the energy of the impinging field is again equally divided between the fields parallel and perpendicular to TE_{10} mode in the guide, with the result that only one-half of the available energy is utilized.

A second special case in which the electric vector of the impinging field is either parallel to or perpendicular to the dielectric wedge will now be considered. Under this condition of wave incidence upon the horn, there is no resolving of the electric vector into components since the vector is already either parallel or perpendicular to the wedge. Inasmuch as both cases of this vector orientation are identical with the exception that in one case the vector is delayed while in the other it is not, only one treatment will be given.

For the explanation of this second special case consider the condition where the electric vector of the impinging field is perpendicular to the dielectric wedge. The original electric vector can then be considered as the vector A. At the far end of the wedge the vector A appears identically the same as at the beginning which means that at this point in the horn the elliptical field of the general case has been reduced to a plane polarized field for this special condition of wave incidence. As the vector A enters the polarizing section it is resolved into two components such that each component is .707 A. One component will be parallel to the TE_{10} mode of the waveguide while the other component is perpendicular. Again only one half the available energy will be propagated down the waveguide with the other being reflected.

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PRNC-3190-10-3-47-100